Uncertainty, risk and dangerous climate change

Recent research on climate change science from the Hadley Centre

December 2004

defra
Department for Environment
Food and Rural Affairs

Met Office
Hadley Centre

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Summary

The Hadley Centre has developed a method to estimate the uncertainty in climate models, the largest source of uncertainty in climate predictions over the next 50 years. Preliminary results suggest that:

- the most likely global average temperature rise for a doubling of the concentration of atmospheric carbon dioxide is predicted to be 3.5 °C, with a 90% probability that the warming will be between 2.4 °C and 5.4 °C;
- at many locations, extreme temperatures are predicted to increase more than the seasonal average. At some locations, seasonal average rainfall is predicted to decrease, while the intensity of extreme rainfall will increase;
- uncertainties in climate change predictions lead to uncertainties in predictions of the impacts of climate change. For plant productivity and water availability, the range of uncertainties is predicted to be greater than the average predicted changes.

Some climate change events have a low probability of occurring in the present day climate but the impacts of these changes could be very large.

- The probability of the oceans' thermohaline circulation collapsing cannot yet be estimated reliably. However, we have simulated the effects of an abrupt collapse of the circulation and it causes significant cooling over much of the northern hemisphere, leading to large impacts.
- A deglaciation of Greenland may be triggered some time in the next few centuries. A new Hadley Centre simulation indicates that more than half of the Greenland ice sheet could be lost over the next 1000 years, with a contribution to sea level rise of up to 4 m.
- During 2003, Europe experienced its most intense heatwave on record, causing more than 15,000 extra deaths. We estimate that man-made climate change has already doubled the risk of such heatwaves. For an IPCC A2 emissions scenario, we predict that by the 2060s such summer temperatures will be unusually cool.

Global land temperatures in 2003 were about 1 °C above the end of the 19th century, making it the third warmest year on record. It was also third in terms of land and sea temperatures together, now about 0.8 °C above the late 19th century.

Introduction

In this report

In this Hadley Centre report, predictions of future climate change and some of its potential impacts are presented, together with estimates of the modelling uncertainty. Uncertainty has long bedevilled the task of planning adaptation to climate change. Now, for a given set of greenhouse gas emissions, instead of a single 'best estimate' prediction, we can present a range of predictions with an indication of the relative likelihood of values within that range. The extra information in these likelihood predictions will, in due course, inform both adaptation and mitigation policies. These initial estimates deal with one of the main causes of model uncertainty. A more complete assessment, with results directly useable by planners and policy makers, is in progress.

There are some potentially high-impact climate events for which we can't yet accurately estimate the risk. However, we can investigate their potential consequences and provide planners of adaptive responses with plausible worst case scenarios. Three potentially high impact events are described in the second part of this report: a collapse of the North Atlantic thermohaline circulation; deglaciation of Greenland; and heatwaves.

In the third section of this report, we present a short bulletin on the state of the climate in 2003 and early 2004, and an update on our regional climate model, PRECIS. This system is now used by countries across the globe to make projections of regional climate change on scales of 50 km.

The Hadley Centre

The Hadley Centre is the United Kingdom's Government centre for climate change science. It is part of the Met Office and located in new headquarters in Exeter. The Hadley Centre employs more than 150 scientific and technical experts, with access to two new NEC SX6 supercomputers. It is financially supported by the Department for the Environment, Food and Rural Affairs (Defra), other Government departments and the European Commission.

The main aims of the Hadley Centre are to:

- monitor climate variability and change on global and national scales;
- attribute recent changes in climate to specific natural and man-made factors;
- understand the processes within the climate system and develop comprehensive climate models which represent them;
- use climate models to simulate global and regional climate change over the last 100 years, and to predict changes over the next 100 years and beyond;
- predict the impacts caused by climate change, such as the availability of water resources and capacity for food production.

Uncertainty in predictions of future climate

Complex climate models with detailed representation of the atmosphere, ocean and land surface are the only tools that can independently predict changes in climate averages and extremes over the planet. The predictions of future climate from these models are being used increasingly to estimate ecological and socio-economic impacts, and to plan adaptive responses. They are also used to evaluate the effect of various mitigation options, such as stabilisation of atmospheric concentrations of greenhouse gases.

All predictions of future climate change contain uncertainties. These are due to unknown future greenhouse gas emissions, uncertainties in the models used to simulate climate change, and because of natural variability (see box below). Being able to quantify the uncertainties in model predictions will enable us to estimate the relative likelihood of different predicted values within the range of uncertainty, and allow the results to be used in quantitative risk assessment methods.

Sources of uncertainty

Uncertain future emissions

Future emissions of greenhouse gases will depend on such factors as future population, energy use and the technology available. We don't know how these will change in future, but it is possible to estimate a range of plausible future storylines, each with its own pattern of emissions. The effect of uncertain emissions on climate can be quantified by making predictions for a range of plausible future emissions, such as the IPCC SRES scenarios.

Uncertain models

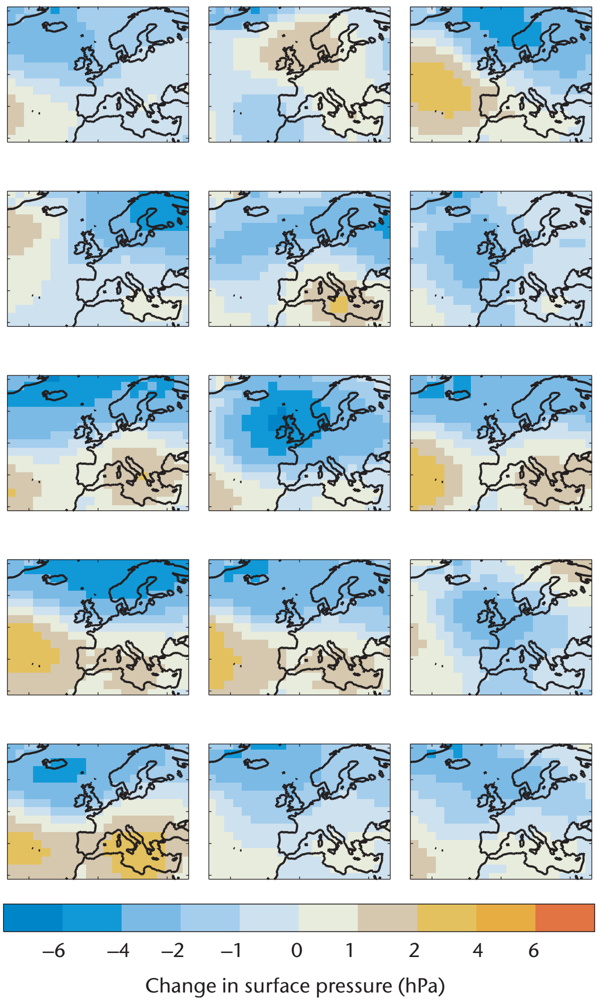
Climate model uncertainty arises from choices made when the models are designed, such as the finest spatial scales that they can represent and the manner in which physical processes in the atmosphere, ocean and land surface are represented. A new technique to estimate the uncertainty in climate model predictions is described in this report.

Natural climate variations

Climate varies naturally on a range of timescales. For a given future period, the natural variability may either add to or subtract from any man-made climate change. Consequently, climate model simulations made with the same climate model and set of emissions, but different plausible initial conditions, will predict a range of future climates.

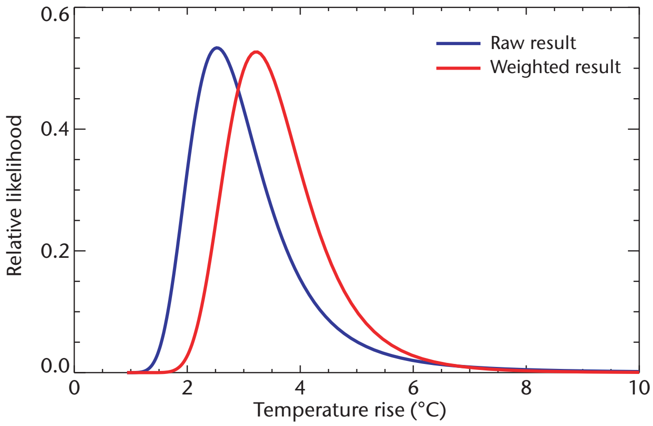
The largest of the uncertainties stem from the climate models themselves; different models give quite different predictions because they represent aspects of the climate system (such as clouds) in different ways. The Hadley Centre has recently developed a method to quantify this climate model uncertainty. This employs many versions of a climate model, each of which uses different, but plausible, representations of climate processes. The model versions are used to predict future changes, with each different version of the model producing a different predicted future climate.

Predicted change in surface pressure over Europe from a subset of the model versions used to generate likelihood predictions



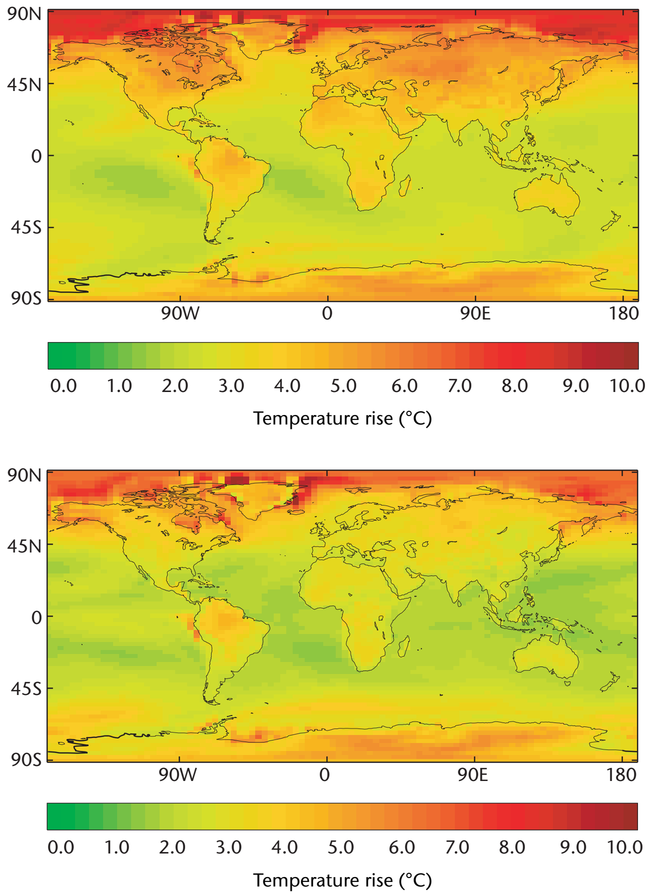
The predicted global average temperature rise for a doubled atmospheric concentration of carbon dioxide (CO_2) is shown in the Figure below. Instead of a single value, a range of future warming is predicted and the relative frequency of each value has been quantified. The Figure also shows how the predictions are modified when they are weighted, using a 'score' based on the ability of model versions to simulate observed present day climate. The most likely warming for a doubling of CO_2 is predicted to be 3.5 °C and there is a 90% probability that the warming will be between 2.4 °C and 5.4 °C.

Global average annual warming predicted by a 53-member model ensemble for a doubling of atmospheric carbon dioxide concentrations



Warming will vary from one location to another. For instance, the land is expected to warm more than the ocean and high northern latitudes are expected to warm particularly strongly (Figure right). Similar spatial variations are also seen in the range of uncertainty, here taken to be the difference between the 5th and 95th percentiles from the warming distribution of the ensemble of models. The greatest range in uncertainty typically occurs where the warming is greatest.

The ensemble average warming (upper panel), and the difference between the 5th and 95th percentiles of the predicted temperature rise (lower panel), from a 130-member ensemble

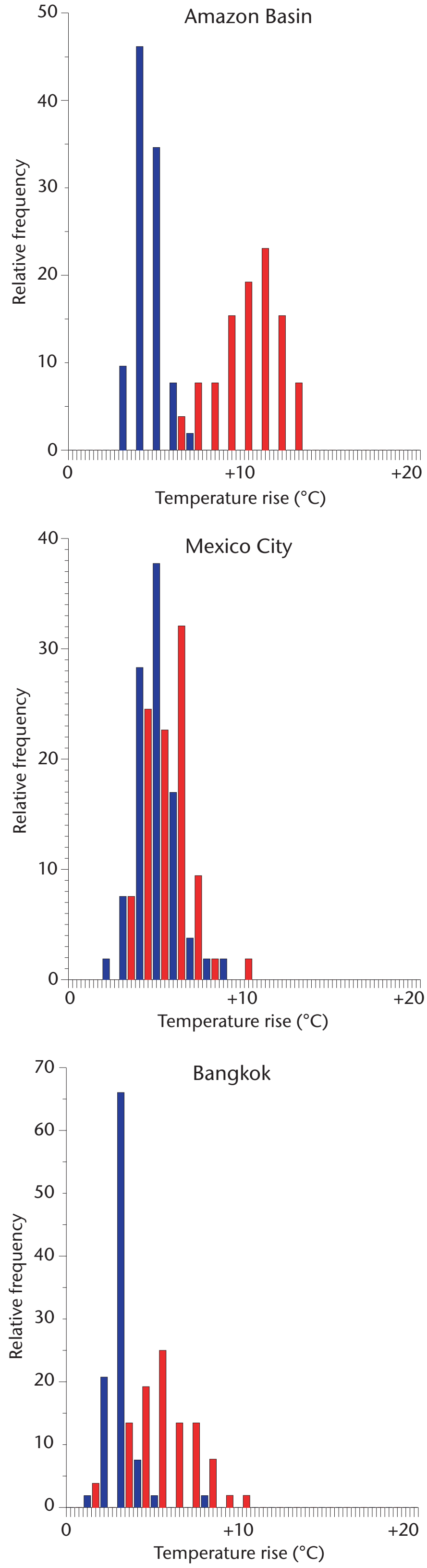


Uncertainty ranges have also been generated for many other aspects of climate. For rainfall, the uncertainty range is larger than temperature, and the largest uncertainties occur at different locations to those of temperature.

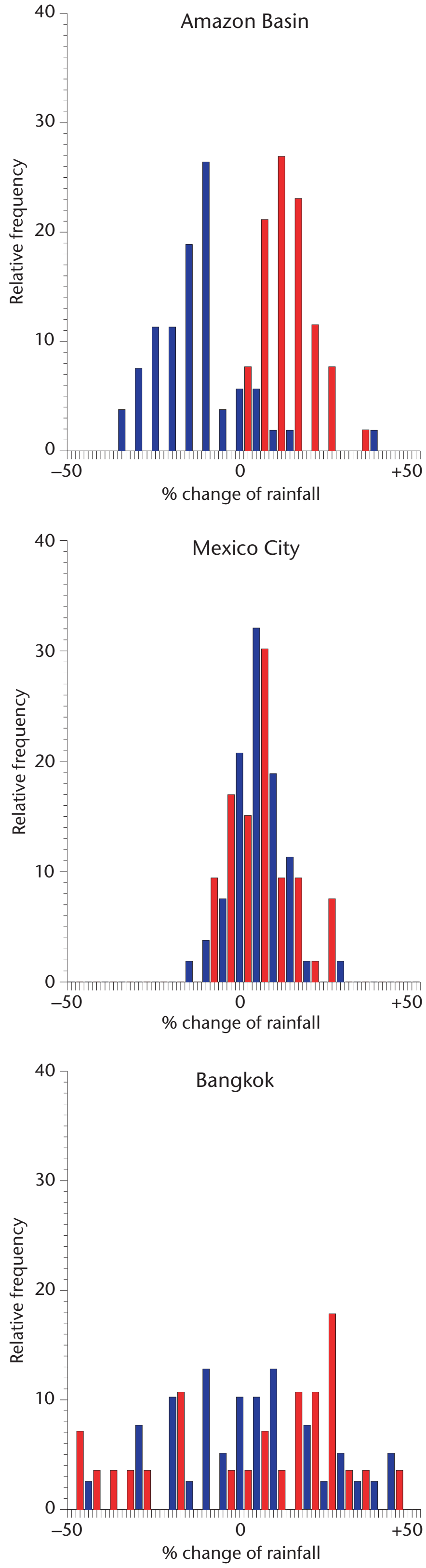
The most serious impacts of future climate change are likely to be caused by changes in extremes. The Figures to the right show the uncertainty in changes in seasonal average and extreme rainfall and temperature, resulting from a doubling of atmospheric CO_2 concentrations. The extreme changes are taken as the change in the temperature or rainfall for the hottest or wettest day of the season of interest.

At some locations, the frequency distributions of the model predictions are narrow and well defined, indicating good predictive ability. At others, especially for rainfall changes in relatively dry conditions, the frequency distributions are wide, suggesting much less predictive skill.

In locations such as Mexico City, the changes in seasonal average climate and extremes are similar. Elsewhere, such as over the Amazon Basin, the changes in seasonal average and extremes are very different, and the extreme warming is usually greater than the seasonal average temperature rise. A more complex situation occurs for the rainfall changes over the Amazon Basin, with the seasonal average predicted to fall, while the intensity of the extreme rainfall is predicted to rise.



Relative frequency of predicted changes in June, July and August daily maximum temperature for the seasonal average (blue bars), and extreme 99th percentile (red bars)



Relative frequency of predicted changes in December, January and February daily rainfall for the seasonal average (blue bars), and extreme 99th percentile (red bars)

The Hadley Centre's climate prediction model is also being used by internet surfers around the world as part of a new international climate experiment — climateprediction.net — organised by the University of Oxford. It works by allowing each user to download their own unique copy of a specially tailored version of the Hadley Centre's global climate model and run it on their own PC. The information is fed back to the Hadley Centre for further analysis. This project will allow us to get results from many more simulations than the Hadley Centre could produce on its own, even using its two supercomputers.

The uncertainty results presented in this report are a new refinement in the technique of making climate predictions with complex climate models. Work still remains to investigate the uncertainty caused by changing more of the model's parameters, including those in the ocean and carbon cycle, or by making large changes in the structure of the model. Before the results are robust enough to be used for planning, it will also be necessary to establish if the more extreme simulated changes are associated with model versions that simulate observed climate well or poorly. The predictions can then be weighted accordingly.

Uncertainty in predictions of climate impacts

The impacts of climate change can be predicted from the results of complex climate model simulations and, like predictions of temperature and rainfall, they are uncertain. Using the ensemble of climate model simulations described on pages 2 and 3, we have estimated uncertainty ranges for predicted future changes in plant productivity and water availability for a scenario of doubled atmospheric CO_2 concentrations.

Plant productivity

The indicator of plant productivity used here is the net primary productivity (NPP), a measure of how much carbon plants can store. It is controlled by the concentration of CO_2 in the atmosphere, temperature, rainfall, and the availability of nutrients, and hence will change in the future.

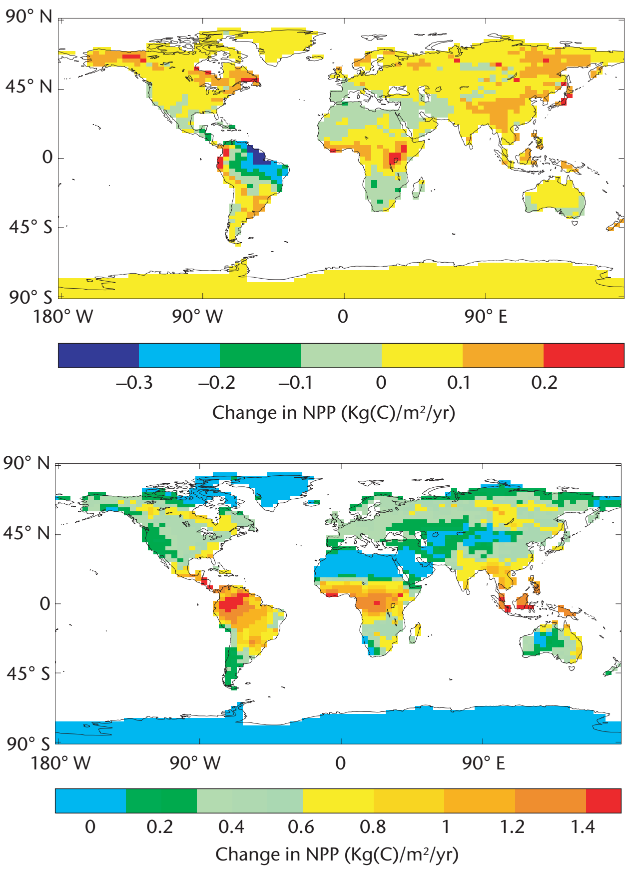
The Figure below (upper panel) shows the changes in plant productivity predicted by the average of the models. As a global average, there is an increase of around 10%. The region with the largest decrease is north-eastern South America.

The sizeable uncertainty range in the predictions of plant productivity is influenced by the potentially competing effects of CO_2 fertilization and climate change. It is also influenced by variations made to the conductance of plant stomata — a parameter in our model of plant behaviour — so that plants in some model versions are not able to benefit from the effects of higher atmospheric CO_2 concentrations.

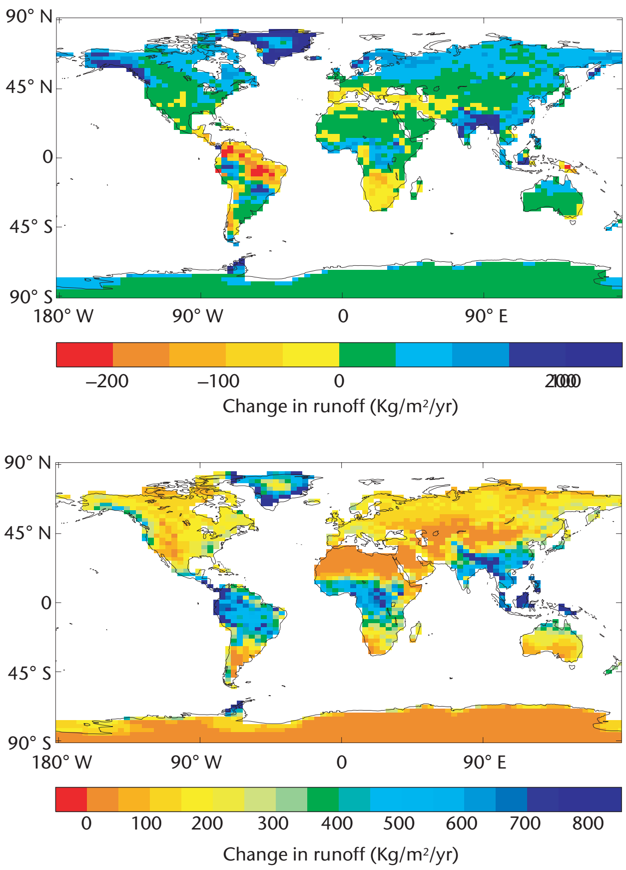
Water availability

Runoff provides a measure of the availability of water in a given region. Changes in runoff predicted by the Hadley Centre climate model are shown in the Figure below. The global average increase in runoff, estimated from the average of the ensemble of models (upper panel), is around 12%. As in the case of plant productivity, the uncertainty in the predicted change in runoff (lower panel) tends to be larger than the average predicted change at most locations.

The average-model prediction (upper panel) and the uncertainty range (lower panel) of plant productivity changes for a doubling of CO_2. The uncertainty range is taken as the difference between the 5th and 95th percentiles



The average-model prediction (upper panel) and the uncertainty range (lower panel) of runoff for a doubling of CO_2



Dangerous climate change

Whilst climate is expected to change gradually over the course of the century, there are some components of the climate system which could change abruptly. There are also concerns that some processes may have a trigger point which, once exceeded, will make the changes inevitable, no matter how much we reduce the emissions subsequently. Such abrupt changes, which are frequently also irreversible, could be considered 'dangerous' in the context of UNFCCC Article 2. Our ultimate aim must be to quantify the risk of these and other, high-impact climate events, although we cannot yet do this accurately for some types of event. What we can do is estimate the global and regional consequences of these events and thus provide plausible worst case climate scenarios for impacts studies and adaptation response planning.

Thermohaline circulation

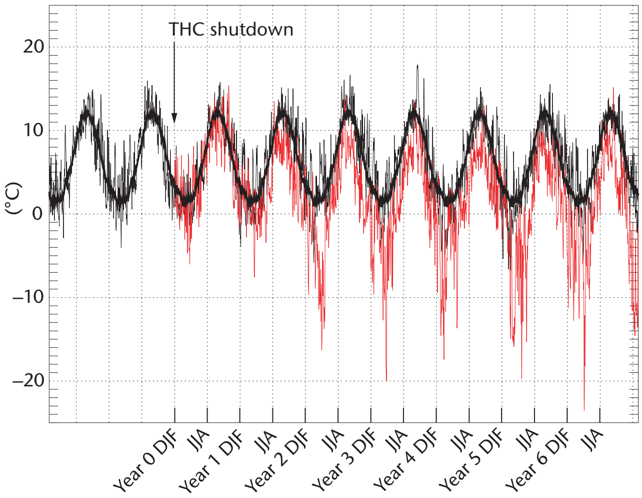
The thermohaline circulation (THC), often called the ocean conveyor, is a system of ocean currents that is responsible for transporting heat from the warm tropics to higher latitudes. Without this heat transport, the climate at mid and high northern latitudes would be considerably colder than at present. The THC is illustrated diagrammatically in the Figure below. The warm surface current in the North Atlantic is often called the Gulf Stream.

The Hadley Centre has recently simulated a world in which the THC has been artificially and rapidly shutdown to find out what the consequences would be on regional and global climate.

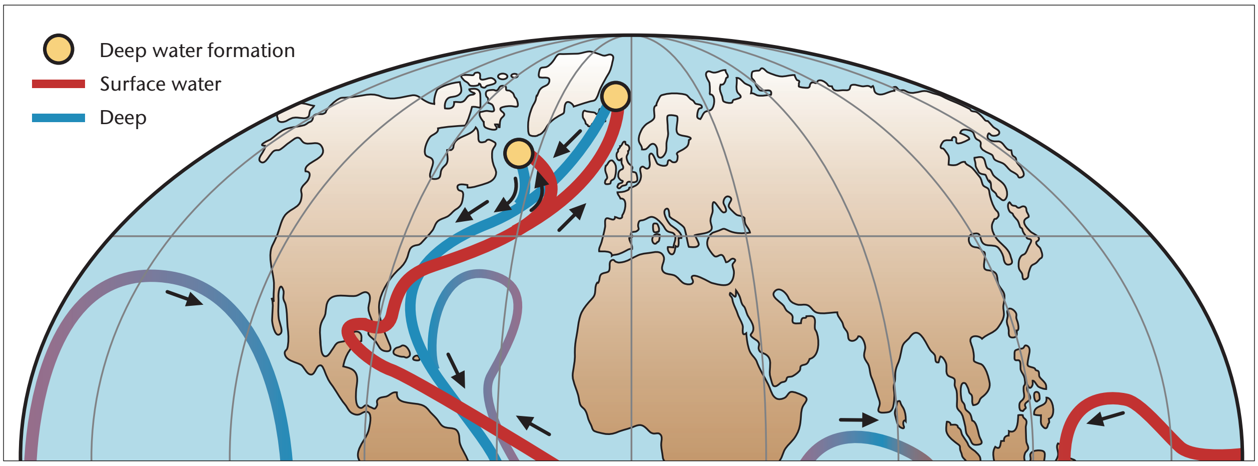
In the 10 years after shutdown, the whole of the northern hemisphere is predicted to cool, with especially strong cooling in and around the north Atlantic. A long-term measure of temperature is the Central England Temperature (CET). Before the THC shutdown, there were very few days when the simulated CET fell below –10 °C. After the shutdown, the CET is predicted to fall below this level several times each winter (Figure below). Changes in other aspects of climate are also likely to occur and, together with the temperature changes, these may have sizeable impacts on, for instance, vegetation and food production.

A new technique is currently being developed to quantify the risk of THC collapse, but the long response times of the ocean circulation make this a challenging task.

Predicted daily minimum CET following an artificial shutdown of the THC. The black curve shows the climate with no THC shutdown. The red curve shows the result after THC shutdown



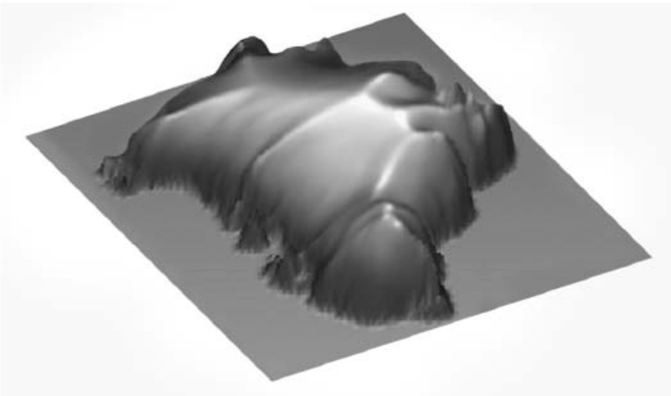
Schematic of the thermohaline circulation. Figure adapted from Rahmstorf, Nature 2002



Greenland deglaciation

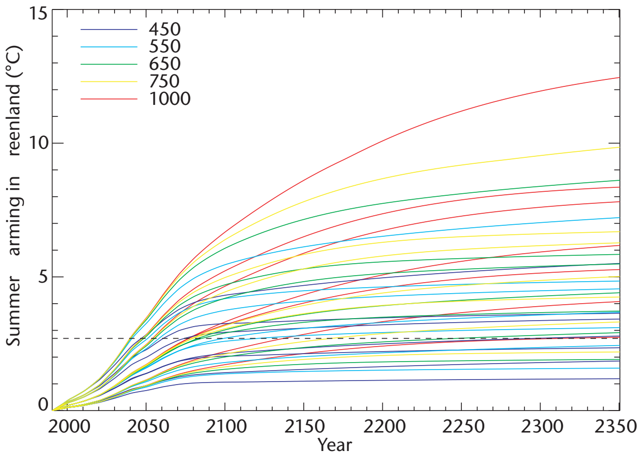
If the Greenland ice sheet were to melt, it would raise global average sea level by around 7 m, which, without upgraded sea defences, would inundate many major cities around the world. There are also concerns that the fresh water from Greenland could help trigger a slow-down or collapse in the THC, leading to cooling over much of the northern hemisphere, and the effects discussed on the previous page.

Present-day elevation of the Greenland ice sheet. The maximum elevation is approximately 3200 m



Previous studies of the Greenland ice sheet have shown that, for a warming of more than 2.7 °C, the ice sheet is likely to contract. We have used a range of climate models, and emissions scenarios leading to stabilisation of atmospheric CO_2 at levels between 450 ppm and 1000 ppm, to show that there is a significant possibility that this trigger point will be reached in coming centuries (Figure below).

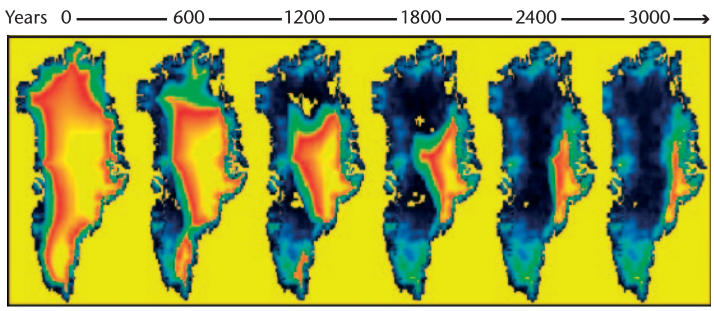
Predicted warming for CO_2 stabilisation levels of 450 ppm, 550 ppm, 650 ppm, 750 ppm and 1000 ppm



To estimate how quickly Greenland could melt and what consequences this might have for regional and global climate, a more detailed model is required. For the first time, a high-resolution model of Greenland has been coupled to the Hadley Centre global climate model to predict how changes in the climate can influence the ice sheet, and changes in the ice sheet can feedback on the climate. The evolution of the ice sheet has been simulated for a pessimistic, but plausible, scenario in which atmospheric CO_2 was increased to four times pre-industrial levels and then stabilised (at around 1100 ppm).

The Figure below shows that the ice sheet would almost disappear over a period of 3,000 years, with more than half of the ice volume melting within the first millennium. The melt water contribution to global sea-level rise would peak at 5.5 mm/year, which is considerably greater than 20th century observed sea-level rise (1 to 2 mm/yr). This rise is in addition to the 3 mm/year of ocean thermal expansion experienced for this scenario.

Predicted change in the ice sheet volume following a quadrupling of atmospheric CO_2. Red indicates thick ice while blue indicates thin (or no) ice



The freshwater provided by the melting of Greenland ice had a small but noticeable effect on the model's ocean circulation, temporarily reducing the thermohaline circulation by a few per cent.

Currently, there is a concern that once the deglaciation process begins, it might not be possible to regrow Greenland to its present volume, even if atmospheric CO_2 was to be reduced to pre-industrial concentrations. We are investigating this in collaboration with colleagues at the Alfred-Wegener-Institut in Germany.

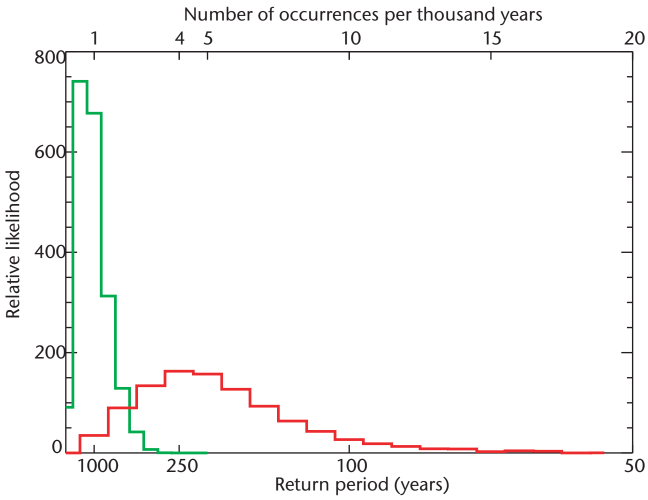
Heatwaves

The European heatwave of 2003 was the hottest since the global instrument record began in 1860. Proxy records suggest it was likely to have been the hottest since at least 1500. The summer temperature over Europe exceeded the 1961–1990 average by 2.3 °C, and that of the previous warmest summer (in 2001) by around 0.7 °C. This exceptionally warm period led to more than 15,000 excess deaths, along with forest fires and large-scale agricultural losses.

There is now strong evidence that global-scale warming in recent decades has been caused by man-made increases in greenhouse gases. However, individual extreme weather events, such as the European extreme heatwave of 2003, cannot be linked directly to climate change because there is a small chance that the events could have occurred naturally. A new approach has been developed by the Hadley Centre, in which we estimate how much the risk of an extreme event occurring has been changed by man-made climate change.

Two climate model simulations were used; one including man-made changes and a hypothetical one without. The uncertainty ranges for each simulation were estimated from a measure of the model's agreement with observations over the 20th century.

Relative likelihood of return periods for the temperature exceeding that of the second warmest European summer, when man-made climate change is included (red), and when it is not (green)*

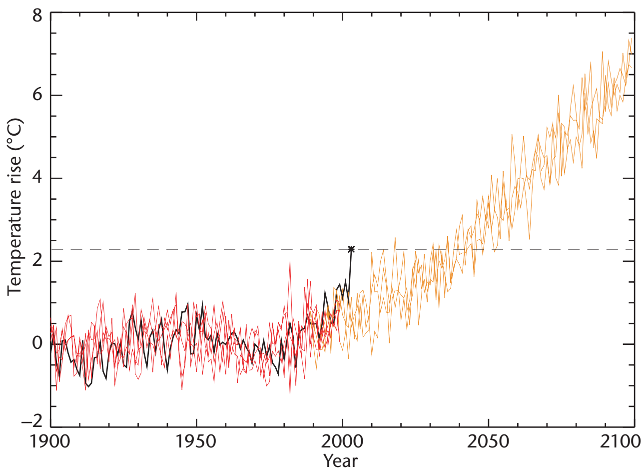


The relative likelihood of exceeding the extreme temperature level when man-made change is included, compared to the case when it is not, has been calculated (Figure below left). The results are expressed as the relative likelihood of the return period of the extreme event taking on various values. When man-made climate change is omitted, extreme warm events are likely to occur very rarely; most likely, once every 1,000 years. However, when man-made changes are included, the same event is likely to occur much more frequently; most likely, once every 250 years.

The increase in the likelihood of the heatwave occurring more frequently, illustrates how man-made climate change has increased the risk of an extreme warm event. Another way of presenting this result is as the fraction of current risk attributable to man-made climate change. It is very likely that at least half the risk of the European 2003 heatwave was due to human activity, mainly fossil fuel burning.

In the future, extreme heatwave events similar to that seen in 2003 are likely to become more frequent because of continued man-made climate change. Using a climate model simulation with greenhouse gas emissions that follow an IPCC SRES A2 emissions scenario, we predict that more than half of all European summers are likely to be warmer than that of 2003 by the 2040s, and by the 2060s a 2003-type summer would be unusually cool (Figure below).

European warming predicted by the Hadley Centre model



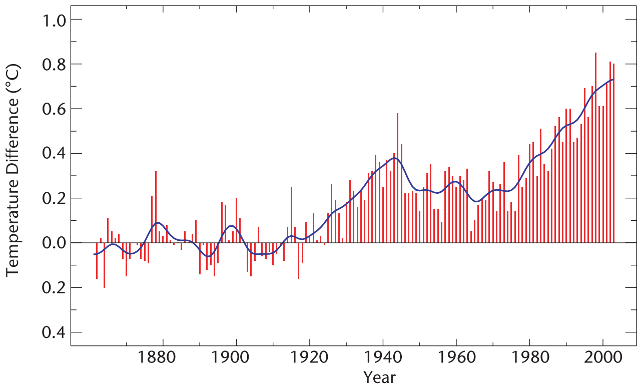
**An event with a return period of 50 years, for example, is expected to occur, on average, once every 50 years.*

Observed climate change

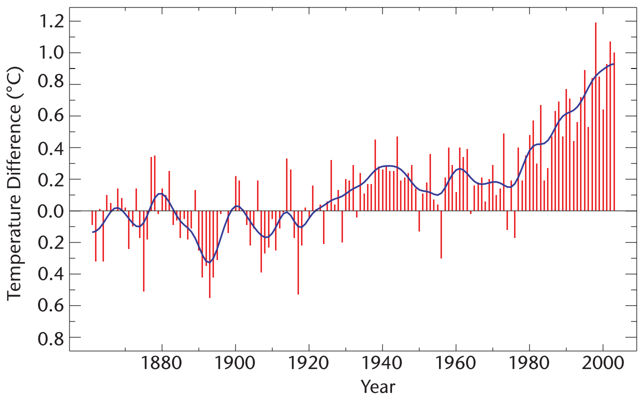
The climate of 2003

The global average surface temperature in the year 2003 was nearly 0.8 °C above the average temperature at the end of the 19th century, making it the third warmest year in the 143-year global instrumental temperature record (see Figures below). The 10 warmest years have occurred since 1990, including each year since 1997. Since 1975, the land has warmed at approximately twice the rate of the oceans.

Observed global average temperatures relative to the end of the 19th century (combined land and sea results)



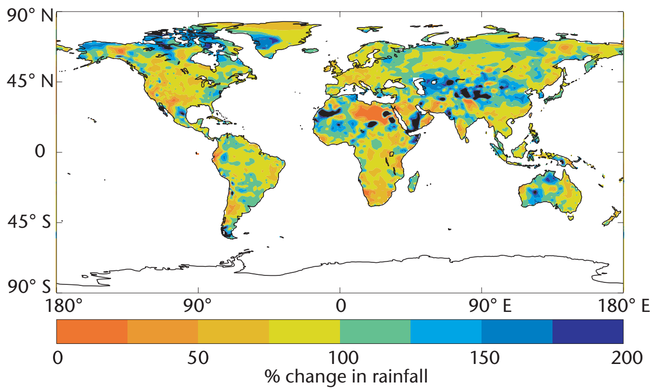
Observed global average land temperatures relative to the end of the 19th century



The long-term annual average number of Atlantic tropical storms, hurricanes and major hurricanes are 10, 6 and 2, respectively, and the storms normally form between the beginning of June and the end of November. During 2003, the hurricane season in the Atlantic was very active, with 16 tropical storms, seven hurricanes and three major hurricanes. In addition, three tropical Atlantic storms formed outside of the hurricane season in 2003. Hurricane activity in the eastern north Pacific was noteworthy because the number of hurricanes was below the long-term average and no major hurricanes formed. However, the number of less intense storms was larger than normal*.

The global average land-surface precipitation fell below normal for the third consecutive year (Figure below). Eastern Australia suffered both extreme heat and severe drought. North America continued to experience drought conditions in the west, whilst to the east, some states experienced record highs of rainfall. Both south-west Asia and the Sahel returned to conditions of near normal rainfall.

Rainfall anomalies for 2003, relative to 1961–90. Raw data provided by Deutscher Wetterdienst

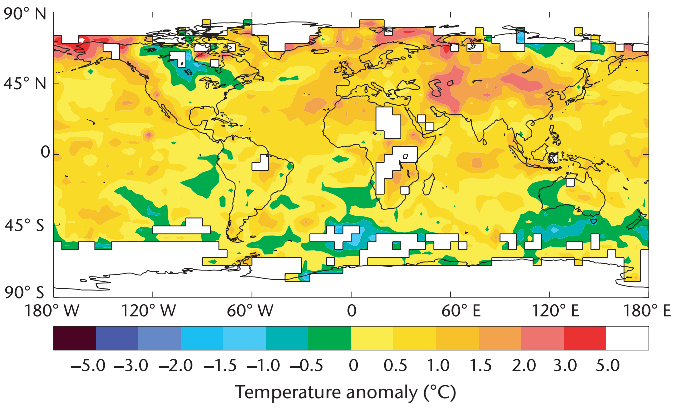


*From the Bulletin of the American Meteorological Society

The climate of 2004

Globally, the temperature for the first nine months of 2004 was 0.7 °C above the annual average temperature at the end of the 19th century (Figure below). Large areas showed significant above-average temperature anomalies over both land and sea, including central Asia and the North Atlantic. In Japan, Tokyo experienced its hottest temperature (39.5 °C) since records began in 1923. Whilst warming is evident in the southern hemisphere, the extent and magnitude is far less than in the north.

Temperature anomalies for Jan–Aug 2004, relative to the end of the 19th century



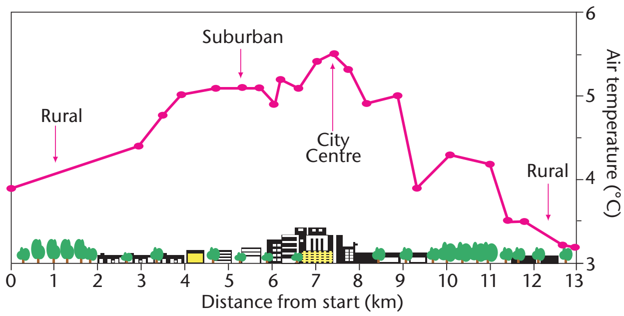
The United Kingdom experienced its wettest August since 1956, with many instances of localised flooding. Current indications suggest that 2004 is likely to be amongst the warmest years on record. This is based on the Central England Temperature, the longest available instrumental temperature record in the world, dating back to 1659.

Urban heat islands

It is well known that temperatures over large urban areas sometimes exceed those in the surrounding countryside, due, for instance, to differences in how much light the ground absorbs, heat storage, different amounts of available surface moisture, and locally produced heat in urban areas. This is the urban heat island effect, and has led to concerns that urbanisation near weather stations may have affected temperature measurements, possibly explaining some of the global warming signal.

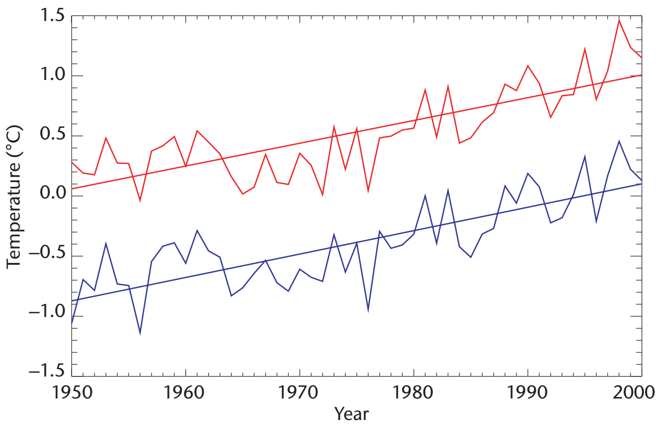
The Hadley Centre has used one of the observed characteristics of urban heat islands — that they mainly occur at night at times when winds are calm — to investigate whether this concern is valid.

Urban heat island



The Figure below shows the increase in the minimum daily temperature, which usually occurs at night, for windy and calm conditions separately. Because the rate of warming is the same during calm and windy periods, these new results indicate that urban heat island effects have not introduced significant biases into estimates of recent global warming trends and, therefore, strengthen our confidence in them.

Trends in the annual average minimum daily temperature at 264 stations separated into calm (blue) and windy (red) conditions



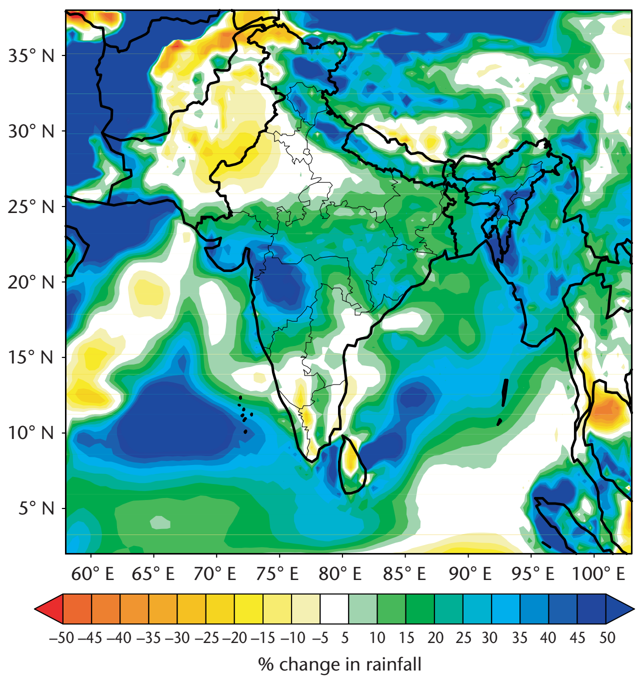
Predicting regional climate using PRECIS

Global climate models can predict future climate on scales of 300 km or more. Regional climate models, driven by output from the global models, provide information on scales of 25 km or 50 km over limited geographical regions, which is more suitable for national climate impact assessments and planning adaptation.

The Hadley Centre has developed a regional modelling software tool that can be deployed over any part of the globe and is easy to set up and use. It also provides training in the use of the model and, more importantly, how to interpret the results, including uncertainties. The PRECIS system (Providing Regional Climates for Impacts Studies) is now installed in more than 40 countries, of which around 35 are UNFCCC non-Annex 1 nations and have received the model and training with support from the UK Government.

The Indian Institute of Tropical Meteorology (IITM) used PRECIS to simulate the changing climate over the Indian subcontinent for two scenarios of future emissions, IPCC SRES A2 and B2.

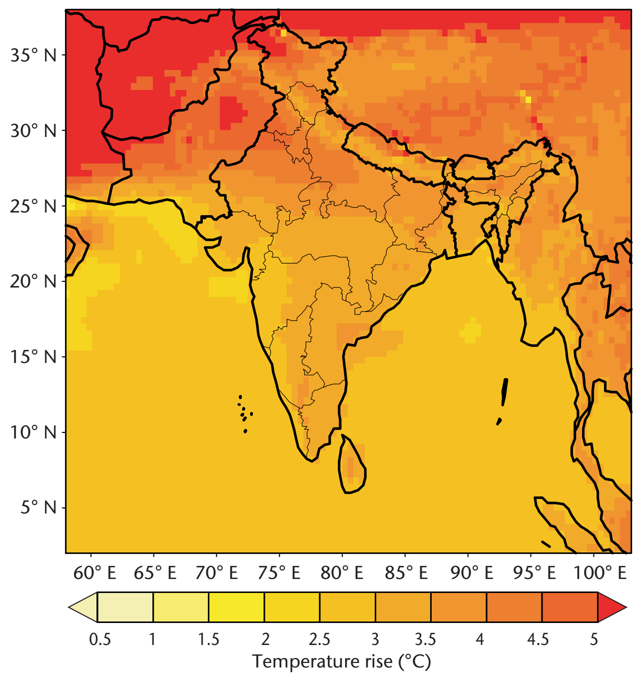
The predicted percentage change in Jun–Sept precipitation between the present day and the 2080s, for the SRES A2 scenario



The above Figure shows the percentage change in rainfall for the June to September season. In the north-west of India and Pakistan, less rainfall is predicted for the future than at present. Conversely, over central India, Bangladesh and Myanmar, increases in rainfall are predicted.

The greatest warming is predicted in the north. In the summer and for the A2 emission scenario (Figure below), the seasonal average temperature over India is predicted to rise by between around 1.5 °C and 4.5 °C by the 2080s, for the A2 scenario.

The predicted change in Jun–Sept temperature between the present day and the 2080s, for the SRES A2 scenario



Results from the PRECIS modelling system, including those produced by IITM and other nations in the Indian subcontinent, are currently being used to estimate climate impacts, such as future river and coastal flooding.

More information on PRECIS can be found at www.precis.org.uk